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Ultra High Energy Cosmic Rays from Axion Stars

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Abstract

We propose a model in which ultra high energy cosmic rays are produced by collisions between neutron stars and axion stars. The acceleration of such a cosmic ray is made by the electric field, $\sim 10^{15}$ $(B/10^{12}\,\mathrm{G})$ eV cm^{-1}, which is induced in an axion star by the strong magnetic field $B > 10^{12}$ G of a neutron star. As we have shown previously, similar collisions generate gamma ray bursts when the magnetic field is much smaller, e.g. $\sim 10^{10}$ G. If we assume that the axion mass is $\sim 10^{-9}$ eV, we can explain huge energies of the gamma ray bursts $\sim 10^{54}$ erg as well as the ultra high energies of the cosmic rays $\sim 10^{20}$ eV. In addition, it turns out that these axion stars are plausible candidates for MACHOs. We point out a possibility of observing monochromatic radiations emitted from the axion stars.

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The origin of ultra high energy cosmic rays (UHECRs) is one of most mysterious puzzles in astrophysics [1]. UHECRs with energies $\sim 10^{20}$ eV can not travel in distance more than 50 Mpc owing to the interactions between UHECRs and the cosmic backgrand radiations. Observations, however, show that there are no visible candidates for the generators of such UHECRs in the arrival directions of UHECRs. On the other hand, dark matter in the Universe [2] is one of most mysterious puzzles in cosmology. Axion [3,4] is a plausible candidate for the dark matter. Probably, some of axions may form boson stars (axion stars) in the present Universe by gravitational cooling [5] or gravitational collapse of axion clumps formed at the period of QCD phase transition [6]. Here we explain a generation mechanism of UHECRs and discuss a production rate of UHECRs assuming collisions between axions stars and neutron stars. We also show that the collisions cause emission of observable monochromatic radiations from the axion stars.

We have previously proposed [7] a possible generation mechanism of gamma ray burst (GRB). According to the mechanism the collision between axion star and neutron star generates a gamma ray burst; the axion star dissipates its mass energy [7,8] very rapidly under the strong magnetic field of the neutron star. Thus, the energy released in the collision is given by the mass M_a of the axion star. Typically it is given by $M_a \sim 10^{-5} M_\odot \, (10^{-5}\text{eV}/m_a)$ where m_a denotes the axion mass. In the analysis we have taken the mass such as $m_a \sim 10^{-5}$ eV as suggested observationally in standard invisible axion models. The mass, $M_a \sim 10^{49}$ erg, corresponding to this choice, however, is not enough to explain a huge energy observed in GRB980123 even if jet is assumed in the GRB.

In this paper, we explain an acceleration mechanism of UHECRs assuming the axion mass, $m_a \sim 10^{-9}$ eV, although the choice is not conventional [2,9]. The essence of the acceleration is that a strong electric field $\sim 10^{15}$ $(B/10^{12}\text{G})$ eV cm^{-1} is induced in the axion star when it is exposed to the magnetic field $B > 10^{12}$ G of a neutron star. This electric field can accelerate charged particles and makes them obtain the huge energies $\sim 10^{20}$ eV. Furthermore, it turns out that the energy $\sim 10^{54}$ erg observed in the GRB can be also explained assuming a moderate jet of the GRB. This is because the mass of the axion star is given by $\sim 10^{-1} M_\odot \simeq 10^{53}$ erg with the assumption of m_a. Thus the collisions between the axion stars and the neutron stars are possible sources of both UHECRs and GRBs. Additionally, it turns out that the axion star is a plausible candidate for MACHO [10] because the value of the mass is suitable for explaining the observations of MACHOs. Since all of baryonic candidates for MACHOs have been argued to have serious difficulties [11], nonbaryonic ones like the axion stars are favored. We discuss that the collisions generate monochromatic radiations with a frequency $m_a/2\pi \simeq 2.4 \times 10^5$ Hz. With the detection of such radiations we can test our model and determine the axion mass.

As we shall show below, we need to separate two cases of the collisions, the collision with a neutron star possessing relatively weak magnetic field $\sim 10^{10}$ G and the one with a neutron star possessing relatively strong magnetic field $> 10^{12}$ G. In the first case the axion star collides directly with the neutron star and dissipates its whole energy inside of the outercrust of the neutron star [7]. The ultra high energy cosmic rays are not produced in this case but gamma ray bursts are produced. On the other hand, in the second case the axion star never collide directly with the neutron star because it evapolates before the collision. This is because the axion star induces a stronger electric field [7,12] when it is exposed to the stronger magnetic field of the neutron star. But such a strong electric field

decays very rapidly owing to electron-positron pair creations [13] when the strength of the electric field goes beyond a critical value. Namely, as the axion star approaches the neutron star, the strength of the magnetic field around it increases gradually and reaches a critical value beyond which the electric field induced in the axion star decays very rapidly. It means that the axion star itself decays very rapidly. In this case the ultra high energy cosmic rays are produced. Gamma ray bursts might be also produced, but they are emitted in a cone with much small solid angle and their duration is very short (less than millisecond).

Let us first explain briefly axion stars (ASs) and how they induce strong electric fields under a magnetic field of a neutron star. The AS is a coherent object of the real scalar field $a(x)$ describing the axion. It is represented by a solution [14,15] of the equation of the axion field coupled with gravity. An approximate form of the solution [15] is given by

$$a(x) = f_{PQ} a_0 \sin(m_a t) \exp(-r/R_a)\,, \tag{1}$$

where t (r) is time (radial) coordinate and f_{PQ} is the decay constant of the axion. The value of f_{PQ} is constrained [2] conventinally from cosmological and astrophysical considerations [2,4] such that 10^{10} GeV $< f_{PQ} < 10^{12}$ GeV (the axion mass m_a is given in terms of f_{PQ} such that $m_a \sim 10^7\ \mathrm{GeV}^2/f_{PQ}$). However, when we assume unconventionally entropy productions below the temperature 1 GeV in the early Universe, we may be released from the constraints [16]. Hereafter we assume that $f_{PQ} \sim 10^{16}$ GeV or $m_a \sim 10^{-9}$ eV.

In the formula, R_a represents the radius of an AS which has been obtained [8,15] numerically in terms of mass M_a of the AS; $R_a = 6.4\, m_{pl}^2/m_a^2 M_a \simeq 1.6 \times 10^5\, \mathrm{cm}\, m_9^{-2}\, (10^{-1} M_\odot/M_a)$, with $m_9 = m_a/10^{-9}$ eV and m_{pl} is Planck mass. Similarly, the amplitude a_0 in eq(1) is represented such as $a_0 = 1.73 \times 10^2\, (10^5\, \mathrm{cm}/R_a)^2\, m_9^{-1}$. Therefore, we find that the solution is parameterized by one free parameter, either one of the mass M_a or the radius R_a. It is also important to note that the solution is not static but oscillating with the frequency of $m_a/2\pi$. It has been demonstrated [17] that there is no static regular solution of the real scalar massless field coupled with gravity. This may be general property of the real scalar massive field.

The AS mass is determined by physical conditions under which the AS has been formed; how large amount of cloud of axions are cooled gravitationally to form the AS, etc.. The situation is similar to other stars such as neutron stars or white dwarfs. A typical mass scale in these cases is the critical mass [18]; stars with masses larger than the critical mass collapse gravitationally into more compact ones or black holes. In the case of the AS, there also exists a critical mass M_c which is given by [14] $M_c \simeq 10^{-1} M_\odot\, m_9^{-1}$ where $M_\odot$ represents the solar mass. Therefore, we adopt this critical mass M_c as a typical mass scale of the ASs. (The critical mass is the maximal mass which ASs can take. Thus, their masses, in general, are smaller than this one. Since energies released in GRBs by the ASs are given by masses themselves, the maximal energy in GRBs is given by the critical mass).

Although the gravitational cooling for star formation is in general ineffective because it is too slow process, it has been shown [5] that the cooling is very effective for the real scalar axion field. Thus, the axion stars can be easily formed gravitationally in a gas of the axions. It is reasonable to assume that the most of the axions in the Universe forms the axion stars.

Let us explain how an AS induces an electric field under a magnetic field $\vec{B}$ of a neutron star. Owing to the interaction between the axion and the electromagnetic field described by $L_{a\gamma\gamma} = c\alpha a(x) \vec{E} \cdot \vec{B}/f_{PQ}\pi$, where the value of c (of the order of unity) depends on axion

models [19,20,4], the Gauss law is modified [21] such that $\vec{\partial}\vec{E} = -c\alpha\vec{\partial}\cdot(a(x)\vec{B})/f_{PQ}\pi +$ "matter". The last term "matter" denotes electric charges of ordinary matters. The first term in the right hand side represents an electric charge made of the axion. (This charge is oscillating and so there exist a corresponding oscillating current, $J_a = c\,\alpha\,\partial_t a(x)\vec{B}/f_{PQ}\pi$. Thus, radiations are emitted by the AS, which might be observable. We will discuss it later.) Thus, we find that the electric field $\vec{E_a}$ is induced; $\vec{E_a} = -c\,\alpha\,a(x)\,\vec{B}/f_{PQ}\pi$ with $\alpha \simeq 1/137$, Numerically, its strength is given by

$$E_a \sim 10^{15}\ \mathrm{eV\ cm^{-1}}\ B_{12}\,m_9 \quad , \tag{2}$$

with $B_{12} = B/10^{12}$ G, where we have used the solution in eq(1) for the critical mass. Obviously, the spatial extention of the field is given by the radius $R_a \simeq 1.6\times 10^5\,m_9^{-1}$ cm of the AS.

This electric field is oscillating with the frequency, $m_a/2\pi \simeq 2.4\times 10^5\,m_9\,\mathrm{Hz}$. Thus a particle with electric charge Ze can be accelerated in a direction within the half of the period, π/m_a or in a distance $\simeq R_a$ ($\sim \pi/m_a \times$ light velocity) by this field, unless it collides with other particles within the period. Thus, the energy ΔE obtained by the particle is given by

$$\Delta E = \mathrm{Ze}\,E_a \times \pi/m_a \times \text{light velocity} \sim 10^{20}\,\mathrm{Z\ eV}B_{12} \quad . \tag{3}$$

Therefore, the electric field can accelerate the charged particle so that its energy reaches $\sim 10^{20}$ Z eV. These charged particles may be baryons or electron-positron pairs produced by the decay of the electric field itself as discussed soon below.

Comment is in order. It seems apparently from eq(3) that stronger magnetic fields yield cosmic rays with higher energies. Stronger magnetic fields, however, induce stronger electric fields, which are unstable against electron-positron pair creations. Therefore, strong magnetic fields do not necessarily yield cosmic rays with higher energies.

If the particles collide with other particles on the way of acceleration, in other words, their mean free paths are shorter than R_a, they can not obtain such high energies. It is easy to see, however, that the mean free paths of quarks or leptons with much higher energies than their masses are longer than R_a in magnetosphere of neutron star. This is because since cross sections, σ, of quarks or leptons with such energies E behaves such as $\sigma \sim 1/E^2$, mean free paths $\sim 1/n\sigma$ is longer than $R_a \sim 10^5$ cm unless number density n of particles around the AB is extremely large (i.e. $n > 10^{40}/\mathrm{cm}^3$).

As is well known, the strong electric field is unstable [13] against electron-positron pair creations. This implies that AS decays into the pairs when the electric field induced in AS is sufficiently strong.

Let us estimate the decay rate of the field and show that the AS decays before colliding with a neutron star whose magnetic field at surface is stronger than 10^{12} G. We also show that the AS can collide directly with a neutron star whose magnetic field is relatively weak $\sim 10^{10}$ G.

The decay rate R_d of the field per unit volume and per unit time is given by [13]

$$R_d = \frac{\alpha E_a^2}{\pi^2}\sum_{n=1}^{\infty}\frac{\exp\left(-m_e^2\pi n/eE_a\right)}{n^2} \tag{4}$$

where m_e denotes electron mass. The rate is very small for an electric field much weaker than $m_e^2\pi \sim 4\times 10^{16}$ eV/cm. The electric field of AS, however, can be very strong and it

can be comparable to $m_e^2\pi$. Therefore, the rate is much large. Numerically, it is given by $R_d \sim 10^{47}\,B_{12}^2\,m_9^2$ cm^{-3}s^{-1} $\sum_{n=1}^{\infty}\exp(-0.7\times 10^2\,n/B_{12}\,m_9)/n^2$. Since the spatial extention of the field is approximately given by $10^5\,m_9^{-1}$ cm, the total decay rate W of the field in AS is $\sim 10^{62}\,B_{12}^2\,m_9^{-1}$s^{-1} $\sum_{n=1}^{\infty}\exp(-0.7\times 10^2\,n/B_{12}\,m_9)/n^2$. Numerically, it reads

$$W \simeq 10/\mathrm{s} \text{ for } B_{12}=0.5, \quad W \simeq 10^6/\mathrm{s} \text{ for } B_{12}=0.55, \quad W \simeq 10^{32}/\mathrm{s} \text{ for } B_{12}=1 \tag{5}$$

with $m_9 = 1$.

Therefore, we find that the AS decays very rapidly (or almost suddenly) when it approaches a region where the strength of the magnetic field reaches a critical value of about 10^{12} G. Hence, the AS evapolates before colliding with the neutron star whose magnetic field at the surface is stronger than 10^{12} G. The whole energy of the AS is transmitted to the charged particles, each of which can obtain energies $\sim 10^{20}$ eV. These particles are emitted into a cone with very small solid angle. They form an extremely short pulse whose width being less than millisecond. Actually, when we suppose that the relative velocity of the AS is equal to light velocity, it decays approximately within a period of 10^{-4}sec $\sim$ 10^{-5}sec; in the period it passes the region where the magnetic field increases from 0.5×10^{12} G to 10^{12} G. These leptons may be converted into baryons and photons through the interactions with themselves, interstellar medium or ejection of progenitor of the neutron star. Thus when the magnetic field is sufficiently strong, ultra high energy cosmic rays can be produced.

We comment that the velocity of AS trapped gravitationally to a neutron star, is approximately given by the light velocity just when it collides with the neutron star. This is because an AS can be trapped to a neutron star when the AS approaches it within a distance $\sim 10^{11}$ cm as we will show below, and then, the AS collides with the neutron star losing its potential energy and angular momentum by emitting gravitational waves. Thus, the velocity of the AS reaches approximately the light velocity when it collides with the neutron star.

Furthermore, we can see from eqs(2) and (4) that the critical electric field depends on the factor of $B_{12}\times m_9$. On the other hand, the energy ΔE obtained by accelerated charged particles depends only on the factor of B_{12}. Therefore, we find that if m_a is smaller than 10^{-9} eV, the maximal energy of cosmic rays can be larger than 10^{20} eV when $B > 10^{12}$ G.

It is easy to see that the decay rate is negligibly small for the case of weak magnetic field $\sim 10^{10}$ G. Thus the AS collides directly with such a neutron star and dissipates the whole energy in the outercrust of the neutron star. Actually, the rate of the energy dissipation in the crust has been estimated previously [7,8] and given approximately by 10^{46}erg/s cm^3, while the energy density of the AS is given by 10^{38}erg/cm^3. Thus even if the velocity of the AS is equal to the light velocity, it dissipates its whole energy in the crust: it never reaches the core of the neutron star. This estimation has been performed by noting that the energy dissipation of the AS arises due to the dissipation of an electric current ($=\sigma_c\,E_a$) induced in the crust with conductivity σ_c; the value of 10^{26}/s has been used for σ_a [22].

Anyway, this collision generates gamma ray bursts with energies $\sim 10^{53}$ erg. The ejection could be emitted into a cone with small solid angle as a jet. This is because particles (mainly irons) of the neutron star are accelerated and emitted in the direction of the strong electric field $\sim 10^{13}\,B_{10}$ eV/cm. The fact that the whole energy of AB is dissipated only in the outercrust, implies that the ejection may be particles composing the crust. Thus a fraction of the baryon contamination in the jet is less than $10^{-5}M_\odot$ as required observationally.

In the above case, the AS dissipates its whole energy in the first collision. On the other hand, an AS may collide several times with a neutron star when its mass is much smaller than the critical mass $\sim 10^{-1}M_{\odot}$. The mass has been assumed as a typical mass of ABs. We see from the general formula of R_a that the radius of the AS with smaller mass than the typical one is larger than the typical radius $\sim 10^5$ cm. For example, if its mass is given by $10^{-2}M_{\odot}$, the radius is about 10^6 cm. This is comparable to the radius of the neutron star. In addition, an electric field induced in such an AS is weaker than the typical one eq(2). This implies that the rate of the energy dissipation in a neutron star is smaller than the one quoted above. In such a case the collisions might occur several times. We expect that these collisions leads to GRBs with pulses of longer duration and softer gamma rays. Observationally the only energies of GRBs with long duration have been measured. We predict that the energies of GRBs with short duration are much larger than those of GRBs with longer duration.

We now wish to estimate an energy release rate per unit volume and per unit time; the energy released as ultra high energy cosmic rays. In order to do so we assume that the dark matter is composed mainly of axion stars. The estimation, however, involves several ambiguities associated with number density of neutron stars, energy density of dark matter or velocity of ASs in the Universe etc. Therefore the estimation does not lead to a conclusive result although our result is consistent with the observations [1].

First we note that luminosity density around our galaxy is observationally given by $2 \times 10^8\,\mathrm{h}\,L_{\odot}/\mathrm{Mpc}^3$ where h is Hubble constant with the unit of 100 km/s Mpc and $L_{\odot}$ represents solar luminosity. We take a mass density ρ corresponding to this luminosity density such as $\rho \sim 10^9 M_{\odot}\mathrm{h}^2/\mathrm{Mpc}^3$. Then, we suppose that the number density of neutron stars is given by $\sim 10^{-2}\rho$. This comes from the fact that the rate of appearance of supernovae is about $0.1 \sim 1$ per 10 years in our galaxy and the age of the galaxy is about 10^{10} years. Probably, the rate of the appearance could be larger in early stage of our galaxy than the one at present. Thus, in our galaxy 10^9 neutron stars might be involved corresponding to the number 10^{11} of stars in the galaxy. Hence we guess that the number of the neutron stars are equal to about 10^{-2} times the number of the stars. All of these neutron stars are assumed to possess strong magnetic field $> 10^{12}$ G. Furthermore, to estimate the rate of the energy release we need to know the average density ϵ of the dark matter. Here we use a value [2] of $0.5 \times 10^{-24}\mathrm{g/cm}^3$, which represents a local density of our halo. Using these parameters we can estimate the rate owing to the collision between the AS and the neutron star if the cross section of the collision is found. The collision cross section for a neutron star to trap an AS is estimated in the following. Namely an AS is trapped by the neutron star when the AS approaches the neutrons star within a distance L_c in which its kinetic energy $M_a v^2/2$ is equal to its potential energy $1.5 \times M_{\odot}\, M_a\, G/L_c$ around the neutron star. G is gravitational constant. Here the mass of the neutron star and the relative velocity v are assumed to be $1.5 \times M_{\odot}$ and 3×10^7 cm/s, respectively. Thus, the cross section is found such as $L_c^2\pi$ with $L_c \simeq 6 \times 10^{11}$ cm. After being trapped, the AS collides with the neutron star by losing its potential energy and angular momentum owing to the emission of gravitational and electromagnetic waves; electromagnetic radiations arise due to the oscillating current J_a. The merger is similar to neutron star - neutron star merger [23]. Time scale from birth to merger is much less than the age of the Universe when the distance L_c between two stars at the birth is given such that $L_c \sim 10^{11}$ cm.

Therefore, we obtain the rate of the collision per Mpc^3 and per year,

$$\epsilon \times 10^{-2}\rho \times L_c^2\pi \times v \times 1\,\mathrm{year}/10^{-1}M_\odot \simeq 3 \times 10^{-9}\,\mathrm{h}^2/\mathrm{Mpc}^3\ \mathrm{year}. \tag{6}$$

Since the energy of $\sim 10^{53}$ erg is released in the collision, we find that the rate of the energy release is given by

$$\sim 3 \times 10^{44}\,\mathrm{h}^2\,\mathrm{erg}/\mathrm{Mpc}^3\ \mathrm{year}. \tag{7}$$

which agrees well with the observed one . Taking account of the fact, however, that there are several ambiguities in the parameters used above and in the observations, we understand that our model can explains roughly the observations [1].

Finally we discuss two possibilities of the observation of the axion stars. One is associated with gravitational lensing and the other one associated with monochromatic radiations from the ASs.

Since we assume that the halo of our galaxy is composed of ASs and their mass is $\sim 10^{-1}M_\odot$, the ASs are plausible candidates for gravitational microlenses, i.e. MACHO. Since baryonic candidates like white dwarfs, neutron stars, etc. have serious problems, nonbaryonic candidates are favored [11]. The problems are associated with chemical abundance of carbon and nitrogen in the Universe: If these baryonic stars are MACHOs, an overabundance of the elements is produced far in excess of what is observed in our galaxy. Hence, the ASs are theoretically the most fascinating candidates for MACHOs since they are also candidates for the generators of both UHECRs and GRBs. If the most favorable mass of the MACHO is $0.5M_\odot$, we need to choose $m_a \simeq 0.2 \times 10^{-9}$ eV since the mass of the ASs is given by $\simeq 10^{-1}M_\odot/m_9$. Smaller axion mass leads to stronger electric field as well as larger mass of AS. Thus, it yields higher energies of the cosmic rays, $\sim 5 \times 10^{20}$ eV and of GBRs, $\sim 5 \times 10^{53}$ erg than the ones we have claimed above. Accordingly, the determination of the mass of MACHOs gives the upper limit of both the energies of the ultra high energy cosmic rays and the energies released in the gamma ray bursts in our mechanism.

We point out another way of the observation of the axion stars. Since the electric field induced in ASs is oscillating, electromagnetic radiations are emitted [15,24] from corresponding oscillating electric current J_a as mentioned above; the frequence of these monochromatic radiations is $\simeq 2.4 \times 10^5\, m_9$ Hz. We expect that such radiations can be detected in advance of UHECRs; they are emitted by the AS revolving around a neutron star before the AS decaying into charged particles. It is easy to estimate their luminocity [24] $\simeq 6.7 \times 10^{41}\, B_{12}^2\,\mathrm{erg/s}$. If the emission arises in a distance ~ 10 Mpc from the earth, we obtain the flux at the earth, $\sim 10^9\,\mathrm{Jy}\,B_{12}^2/m_9$; we have assumed that the velocity of the AS revolving is $\sim 0.1\times$ light velocity. Although the possibility of observing the radiations is very intriguing, it might be difficult to detect the radiations with such a low frequency because they could be absorbed by interstellar ionized gases.

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REFERENCES

[1] M.A. Lawrence et al. J. Phys. G. Nucl. Part. Phys. 17, 773 (1991),
D.J. Bird et al. Phys. Rev. Lett. 71, 3401 (1993); ApJ 424, 491 (1994),
N. Hayashida et al. Phys. Rev. Lett. 73, 3491 (1994),
M. Takeda et al. Phys. Rev. Lett. 81, 1163 (1998); ApJ, 522, 225 (1999).

[2] For a review, see, for example, E.W. Kolb and M.S. Turner, The Early Universe, Addison-Wesley, New York, (1990).

[3] R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. 38, 1440 (1977),
S. Weinberg, Phys. Rev. Lett. 40, 223 (1978),
F. Wilczeck, Phys. Rev. Lett. 40, 279 (1978).

[4] J.E. Kim, Phys. Rep. 150, 1 (1987).

[5] E. Seidel and W.M. Suen, Phys. Rev. Lett. 72, 2516 (1994).

[6] E.W. Kolb and I.I. Tkachev, Phys. Rev. Lett. 71, 3051 (1993);
Phys. Rev. D49, 5040 (1994).

[7] A. Iwazaki, Phys. Lett. B455, 192 (1999).

[8] A. Iwazaki, Phys. Rev. D60 025001 (1999).

[9] T. Banks and M. Dine, Nucl. Phys. B479, 173 (1996); Nucl. Phys. B505, 445 (1997).

[10] C. Alcock et al. Astrophys. J. 449, 28 (1995),
for a review, see C.S. Kochanek and J.N. Hewitt, eds, "Astrophysical Applications of Gravitational Lensing", IAU Symp. 173 (1996) (Kluwer, Dordrecht).

[11] see, for example, F. Katherine astro-ph/9901178.

[12] A. Iwazaki, Prog. Theor. Phys. 101, 1253 (1999).

[13] J. Schwinger, Phys. Rev. 82, 664 (1951).

[14] E. Seidel and W.M. Suen, Phys. Rev. Lett. 66, 1659 (1991).

[15] A. Iwazaki, Phys. Lett. B451, 123 (1999).

[16] P.J. Steinhardt and M.S. Turner, Phys. Lett. B129 51, (1983).

[17] P. Jetzer, Phys. Rep. 220, 163 (1992),
T.D. Lee and Y. Pang, Phys. Rep. 221, 251 (1992),
A.R. Liddle and M. Madsen, Int. J. Mod. Phys. D1, 101 (1992).

[18] S.L. Shapiro and S.A. Teukolsky, Black Holes, White Dwarfs, and Neutron Stars, A Wiley-Interscience Publication, (1983).

[19] A.R. Zhitnitsky, Sov. J. Nucl. Phys. 31, 260 (1980),
M.D. Dine, W. Fischler and M. Srednicki, Phys. Lett. B104, 199 (1981).

[20] J. E. Kim, Phys. Rev. Lett. 43, 103 (1979),
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B166, 493 (1980).

[21] P. Sikivie, Phys. Lett. B137, 353 (1984).

[22] N. Itho et al. ApJ 418, 405 (1993),
D.A. Baiko and D.G. Yakovlev, Astron. Lett. 72, 702 (1995); astro-ph/9604164.

[23] T, Totani, ApJ. 511, 41 (1999).

[24] A. Iwazaki, hep-ph/9908468.